Probing Electronic States of Magnetic Semiconductors Using Atomic Scale Microscopy & Spectroscopy

Ali Yazdani, Princeton University
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Objective: This project was focused on the application of the scanning tunneling microscopy (STM) to understand the electronic structure of magnetically doped semiconductors and to develop the means to examine the magnetism and its influence on electronic properties on the atomic scale in semiconductors.

Activities: The program started with examination of individual Mn acceptors in GaMnAs, which is the magnetic semiconductor with the highest transition temperature discovered to date. Spectroscopic measurements provided detailed information on the nature of Mn acceptor states that both introduce carriers and magnetism to this semiconductor. These initial studies focused on Mn acceptors near the surface that were implanted by using STM atomic manipulation techniques. Following this understanding of single and pairs of acceptors, the program then focused on MBE grown heterostructures using samples of ferromagnetic GaMnAs that were specifically designed for STM studies. The work performed by this program provided the first real space perspective of these compounds, demonstrating the absence of clustering of Mn acceptors in the best prepared MBE samples, as well as illustrating the role of electronic heterogeneity of electronic structure in the development of carrier-mediated magnetism in this compound. STM studies made possible the first real space statistical analysis of the electronic properties of this compound, showing that proximity to the metal-insulator transition results in log-normal distribution of electronic density of states at the chemical potential. We demonstrated that this distribution was also correlated with the divergence of a characteristic length scale as expected for the structure of a critical wavefunction near the metal-insulator transition. Remarkably, we were able to confirm the fractal nature of quantum wavefunction near the metal-insulator transition, a feature that has long been predicted theoretically. We showed that a similar picture is at play in magnetic doping of narrow band gap topological insulators by carrying out similar measurements on Mn-doped Bi_2Te_3 and Mn-doped Bi_2Se_3 compounds. Our goal with these experiments, in addition to extending the picture of magnetism to another semiconductor system, has been to probe the influence of magnetic ordering on topological insulators and their surface states.

This ONR program also partially supported our efforts in the studies of surface states of topological insulators. One of the studies demonstrated that the spin-momentum locking results in the absence of backscattering for these topological surface states, while another study showed that they can penetrate through barriers that blocks other surface states. We also examined the role of chemical potential fluctuations in real space variations of electronic properties of these compounds, caused by charged impurities, which strongly influences their transport properties.

This ONR program additionally provided the initial funding for us to develop a new platform for the development of topological superconductivity that can host Majorana fermions. Initial theoretical calculations carried out under this program showed that chains of magnetic atoms on the surface of a superconductor can be used as a versatile platform for creating a topological superconductor. These initial efforts provided the motivation for us to pursue this research direction and shifted our group's focus to the current ONR program on detection and manipulation of Majorana fermions in a condensed matter setting.

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This project was focused on the application of the scanning tunneling microscopy (STM) to understand the electronic structure of magnetically doped semiconductors and to develop the means to examine the magnetism and its influence on electronic properties on the atomic scale in semiconductors.

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Finally, another major breakthrough for our program has been the development of a spin-polarized STM instrument that can carry out experiments in a vector magnetic field. This instrument can operate in temperatures down to 1K in vertical fields up to 6T and a vector field of 1T. While the funding for this instrumentation has been provided by other grants (from the Keck foundation), the ONR support was critical to get this instrument running and to carry out initial spin-polarized experiments. Coating the tip with a magnetic layer, we have been able to carry out systematic experiments on Fe islands on Cu to test our ability to make measurements of single domain ferromagnetic islands on the metal surface. The *in situ* application of a vector magnetic field provides an important experimental capability to ensure that the STM contrast measured is in fact due to magnetism.

Summary of the most notable accomplishments:

- Mapping the wavefunction of transition metal acceptors states in GaAs
- Demonstrating absence of clustering in MBE grown GaMnAs samples
- Importance of electronic heterogeneity in the electronic properties of GaMnAs
- Visualizing critical correlations near the metal-insulator transition in GaMnAs
- Demonstration of the absence of backscattering in topological surface states
- Study of the ferromagnetism in doped topological insulators
- Visualizing the spatial fluctuations of helical Dirac fermions on the surface of a topological insulator
- Proposing a novel platform for topological superconductivity and Majorana fermions in a chain of magnetic atoms on the surface of a superconductor

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1. H. Beidenkopf, P. Roushan, and A. Yazdani, “Visualizing topological surface states and their novel properties using scanning tunneling microscopy and spectroscopy,” invited chapter in *Topological Insulators*, edited by M. Franz and L. Molenkamp, Elsevier (2013).
2. S. Nadj-Perge, I.K. Drozdov, B. A. Bernevig, and A. Yazdani, “Proposal for realizing Majorana fermions in chains of magnetic atoms on a superconductor,” Rapid Communication in Physical Review B **88**, 020407 (2013).
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